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INDICATOR TESTS FOR THE CREEP OF ROCK SALT FROM
BOREHOLE MOSS BLUFF 2, MOSS BLUFF DOME, TEXAS

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Abstract

Creep tests were performed on a representative sample of rock salt from Moss Bluff 2 (MB2), Moss Bluff dome near Houston, Texas. MOSS Bluff 2 is located at the site of a compressed gas storage cavern of Tejas Power Corporation. Four triaxial experiments were conducted at two values of principal stress difference and two representative temperatures. The minimum observed creep rates at the end of each test varied between 5.2×10^{-9} 1/s and 2.14×10^{-8} 1/s. Comparisons of the present results with existing data for rock salt from other locations suggest that the steady-state creep characteristics of MB2 salt, depth 3349 ft (1098.8 m), are intermediate to those measured for the U.S. Strategic Petroleum Reserve at West Hackberry and Bryan Mound, which included the most creep resistant rock salt ever tested at Sandia National Laboratories. Creep parameters are suggested for first-order sensitivity calculations.

Acknowledgements

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Contents

Introduction.....	7
Available Core and Sample Preparation.....	7
Selection of Test Parameters.....	8
Apparatus and Test Procedures.....	11
Experimental Results.....	13
Discussion of Results.....*	19
Summary and Conclusions.....	20
References.....	21
Figures	
1 - Undeformed and laboratory deformed rock salt samples from borehole Moe Bluff 2, depths 3349 ft (1098.8 m) and 3350 ft (1099.1 m).....	9
2 - Schematic of typical triaxial creep apparatus in Rock Mechanics Laboratory, Sandia National Laboratories. Major components: (1) tie rods on base plate, (2) hydraulic actuators, (3) pressure vessel, (4) deviatoric loading piston, (5) Belleville washers, (6) heaters, (7) insulation, (8) cross head with guide rods, (9) frame extension/lifting fixture, (10) thermocouple location.....	12
3 - Strain-time (creep) record for four creep experiments conducted on sample Moss Bluff 2, 3349 ft (1098.8 m) over a period of 1684 hours (70 days). Tail of curve was recorded during unloading and cooling portion of test. Steady-state creep estimates were set equal to the slope $\frac{de_1}{dt} = \dot{\epsilon}_1$ near the end of each test	14
4 - Plot of principal stress difference, $\tau = (\sigma_1 - \sigma_3)$, and confining pressure, σ_3 , versus time for triaxial creep experiments on Moe Bluff 2, 3349 ft (1098.8 m) over a period of 1684 hours (70 days). See also Figure 3.....	15
5 - Comparison of creep data for rock salt from Moss Bluff 2, 3349 ft (1098.8 m) with power-law fits to different sets of measurements on rock salt from the bedded Salado formation, southeastern New Mexico (WIPP4C and WIPP7), West Hackberry dome (WH1 and WH2), Bryan Mound dome (BM3C and BM4C), and Bayou Choctaw (BC1). All measurements and data fits represent steady-state creep estimates at the end of each test, ϵ_1 , normalized to creep at 140°F (60°C). Power-law parameters used for comparison data are published in Reference [2].....	18
Tables	
1 - Sample Data, Test Parameters, and Creep Measurements for MB2.....	16

Introduction

In March, 1992, a cursory evaluation was requested of the creep response of rock salt from the Moss Bluff salt dome located approximately 40 miles (64 km) East of Houston, Texas. The core was taken in borehole Moss Bluff 2 which will be used by Tejas Power Company to create a gas storage cavern by means of solution mining. The borehole Moss Bluff 2 (MB2) is located in the North Central part of the 2.5-mile (4-km) diameter dome and some 1000 ft (328 m) East from an existing cavern, Moss Bluff 1 (MB1). MB1 was developed in 1980 and abandoned thereafter until 1989 when it was acquired by Tejae Power Company. MB 1 currently holds approximately 2.5 MMb of compressed natural gas. The new cavern Moss Bluff 2 will be substantially larger with a design capacity of 6.2 MMb. The new cavern will have a nominal height and diameter of 1600 ft (525 m) and 200 ft (66 m), respectively. The roof of MB2 will be placed 2500 ft (820 m) below surface and some 900 ft (295 m) below the top of the salt.

Salt core from Moss Bluff 2 was received by Sandia National Laboratories (SNL) in mid-April, 1992, for sample selection, sample preparation, and creep testing in the SNL Rock Mechanics Laboratory. Actual tests were performed during the period May 13 to July 25, 1992. This report summarizes the rationale of the measurements, associated facilities and test procedures, and the creep data obtained. The available but limited measurements are then compared with an existing data base for rock salt from the bedded Salado formation in southeastern New Mexico and from three salt domes and sites of storage caverns of the U.S. Strategic Petroleum Reserve (SPR) program.

It is emphasized that the results in this report were obtained from limited measurements on a single piece of core. Although the quality of the measurements is deemed excellent, the duration of several of four sequential creep tests was too short to yield unambiguous data.

Available Core and Sample Preparation

Core was received from depths of 2511 ft (824 m) to 3783 ft (1241 m). From this, the section 3349-3350 ft (1099.8-1099.1 m) was selected for testing because it represented salt from the central portion of the cavern. The salt core is medium gray in color and has an average grain size of approximately 0.4 in (11 mm). Individual grains were slightly elongated and aligned along a dip direction of 28" from vertical.

Two samples were machined on a band saw and lathe to final nominal dimensions 8.1 in (20.6 cm) long by 3.9 in (9.9 cm) diameter. The quality of a difficult sample preparation process was indicated by sharp edges around the ends of the cylindrical samples. After machining, the samples were coated with a thin layer of brush-on silastic, greased with molybdenum disulfide across the ends, placed between mirror-polished stainless steel end cape, and enclosed in a flexible neoprene jacket. A thermocouple was

placed through one end cap into a small hole about one inch deep into the sample to ensure good temperature measurements during the experiments later.

The undeformed sample 3350 is shown on the right in Figure 1 next to sample 3349 after testing. The considerable lighter appearance of sample 3350 is caused by light reflection from a myriad of small cracks (primarily along grain boundaries), almost all of which are created during the process of coring and core extraction in situ. Some additional cracking during laboratory sample preparation is and was unavoidable.

Selection of Test Parameters

It is generally believed that the long-term behavior of rock salt cannot be predicted from short-term, so-called quasi-static tests. Instead "rate tests" are required either at constant deformation rate or at constant stress. Contrary to assumptions sometimes made in the past, it is also accepted that assessments of rock salt properties cannot be accelerated by arbitrarily raising temperature and stress. Instead, stress and temperature must be carefully chosen in order to trigger the same and no other micromechanical processes in laboratory experiments that are also rate-controlling in the engineering application in situ [1-3]. Hence, rock salt exhibits the same drastic change in mechanical response which fascinates, for example, young students about silly putty. When struck by the hard blow of a hammer, silly putty shatters in a brittle fashion; yet, silly putty cannot maintain its shape and will "flow" like dough under the seemingly minor action of its own weight.

Creep experiments in this study were carried out at temperatures of 104°F (40°C) and in 140°F (60°C) which are representative of temperatures at most in situ storage locations. The stresses driving creep, $\tau = (\sigma_1 - \sigma_3)$, were nominally 2300 psi (15.9 MPa) and 2800 (19.3 MPa) where σ_1 and σ_3 denote the greatest and least applied principal compressive stresses. In axisymmetric triaxial compression tests, σ_3 is the confining pressure which was set at 2000 psi (13.8 MPa).

Creep of materials, including rock salt, is characterized by a transient (time-varying) response for some time and through some deformation after the stresses are applied [1]. This type of behavior is referred to as transient or primary creep whose rate will decrease with time following stress increases. The transient creep rates have been observed to increase or decrease with time after stress reductions depending on the exact previous deformation history [4].

If constant stress conditions are maintained long enough, then transient creep will lead to a condition of steady-state creep. The constant steady-state creep rate is assumed to be independent of the material history and solely determined by the values of the current stresses and temperature besides intrinsic properties like chemical

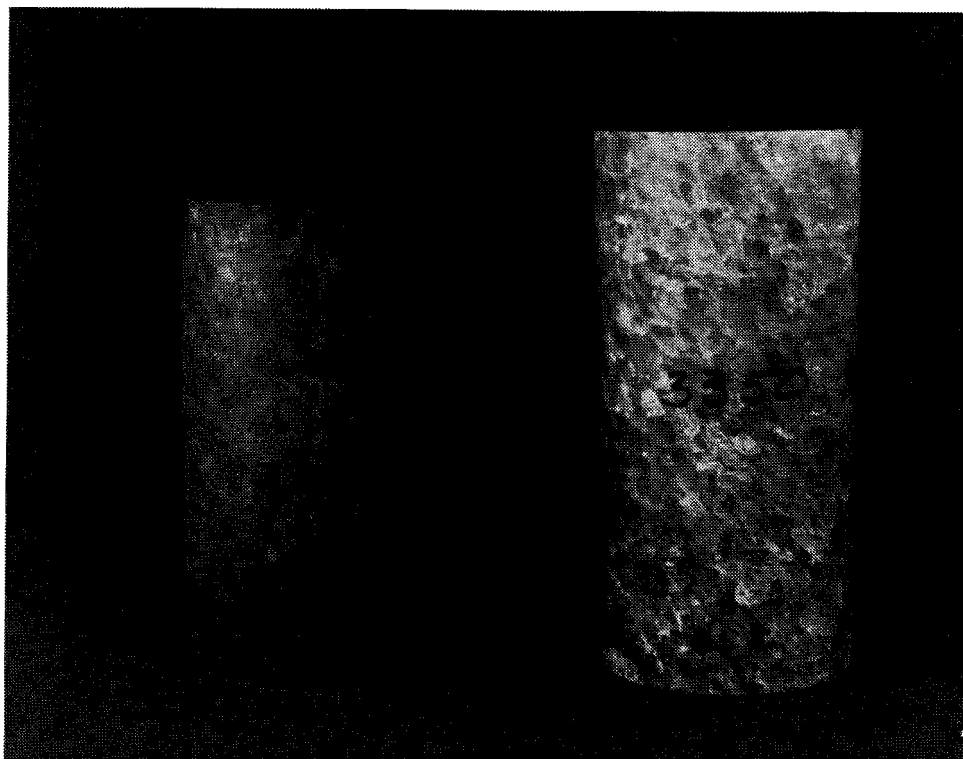


Figure 1 - Undeformed and laboratory deformed rock salt samples from borehole Moss Bluff 2, depths 3349 ft (1098.8 m) and 3350 ft (1099.1 m)

composition. In order to compare the long-term behavior of salt from different locations, therefore, it appears best to compare steady-state creep rates. Unfortunately, at this point, steady-state creep measurements at representative conditions require long test durations, measurements of extremely low deformation rates, and the very difficult decision concerning when creep rates no longer change with time. Because it is known, however, that deformation and time at a lower stress count towards the total transient creep accumulation at any higher stress, it is prudent to perform creep tests at different stresses on the same sample in sequence and in the order from low to high stress [4].¹ Carrying out several measurements on the same sample of natural (as opposed to a closely controlled, man-made) material offers the added advantage that variations in measurements are not likely to be affected by changes in sample composition, texture, or structure.

The foregoing rationale guided the selection of test conditions for MB2 salt. However, in order to appreciate all test values, one more fact is important. A large body of data for rock salt suggests that an acceptable model for steady-state creep can be derived from the simple expression for the steady-state rate of greatest compressive strain [1,2,5-6].

$$\dot{\epsilon}_1 = A \exp(-Q/RT) (\tau/\mu)^n \quad (1)$$

Equation 1 indicates that creep is a strong function of temperature, T (in degrees Kelvin), i.e., it is thermally activated. The rate-controlling property is the activation energy Q (Cal/mole or J/mole). The parameters A and n are constants, and R is the universal gas constant, R=1.99 cal/K mole (8.32 J/K mole). $\mu=1.8 \times 10^6$ psi (12.4 GPa) is a typical value of the elastic shear modulus of rock salt.

It is noted that good fits of Equation 1 to creep data do not prove that the steady-state creep of rock salt is governed by intracrystalline, diffusion-controlled climb of edge dislocations as is frequently suggested. Nevertheless, Equation 1 was used here because it is known [2] that modest extrapolations of this model beyond laboratory conditions appear to differ little from alternative models which are derived for micromechanical mechanisms other than climb-controlled creep.

Equation 1 implies that Q and the so-called power law stress exponent, n, can be computed by means of steady-state creep measurements at two stresses and two temperatures. Accordingly, the nominal experimental conditions for sample MB2 3349 ft (1098.8 m) were chosen as follows:

¹ It is important that the interpretation of creep tests following stress reduction requires a mathematical model which does not only describe decelerating transient creep but also accelerating transient creep with a different characteristic time.

$$\begin{aligned}
 (\sigma_1 - \sigma_3) &= 2300 \text{ psi (15.9 MPa) and } 2800 \text{ psi (19.3 MPa)} \\
 \sigma_3 &= 2000 \text{ psi (13.8 MPa)} \\
 T &= 104^\circ\text{F (40}^\circ\text{C) and } 140^\circ\text{F (60}^\circ\text{C)}
 \end{aligned}$$

Apparatus and Test Procedures

The MB2 creep tests were carried out in a triaxial apparatus very similar to the test frame shown in Figure 2. The minor differences in the systems shown and used are fourfold. (1) The hydraulic actuator for axial sample loading was located on top rather than below the pressure vessel, and the four column load frame in Figure 2 was replaced by a threaded ring connection between a compact (10,000 psi; 69.8 MPa) actuator and the pressure vessel. (2) One end (the bottom end) of the pressure had a threaded closure with electrical feedthroughs. (3) The pressure vessel wall was heavier for tests to higher pressures. (4) The sample was enclosed in a neoprene jacket which is less costly than Viton and equally suitable for use up to 212°F (100°C).

Note that the nipples in the end caps in Figure 2 provide access to the sample and made it possible to insert a thermocouple and monitor sample temperature directly with time. Sample heating is accomplished by external sheet heaters around the pressure vessel and a cartridge heater inside the movable axial loading piston. Optional two- or three-zone heater control is accomplished by means of three thermocouples placed in the pressure vessel closure, about one-half the thickness into the pressure vessel wall, and near the end of the movable loading piston inside the pressure vessel.

Pressure, load, and axial deformation (strain) measurements were made external to the pressure vessel. Note that the lateral (diametral) sample deformations were not measured based on earlier observations that the volumetric rock salt deformations in SPR laboratory creep tests are much smaller than the shear deformations which govern cavern closure [7]. Individual calibrations are traceable to national standards and are checked before and at the end of each experiment.

Test control is done by means of programmable microprocessors which maintain axial load (stress), confining pressure, stress difference, τ , and temperature within close tolerances. In the present tests, axial stress and confining pressure varied by less than ± 20 psi (0.14 MPa) and ± 3 psi (0.02 MPa), respectively. Some spikes in the data records are the result of electronic noise rather than real stress changes. Temperature was held constant to within $\pm 0.18^\circ\text{F} (\pm 0.1^\circ\text{C})$. The difference between temperature at the control thermocouple locations and at the thermocouple location in the rock salt sample was $0.36^\circ\text{F} (0.2^\circ\text{C})$ at nominally 104°F (40°C) and $2.21^\circ\text{F} (1.2^\circ\text{C})$ at nominally 140°F (60°C).

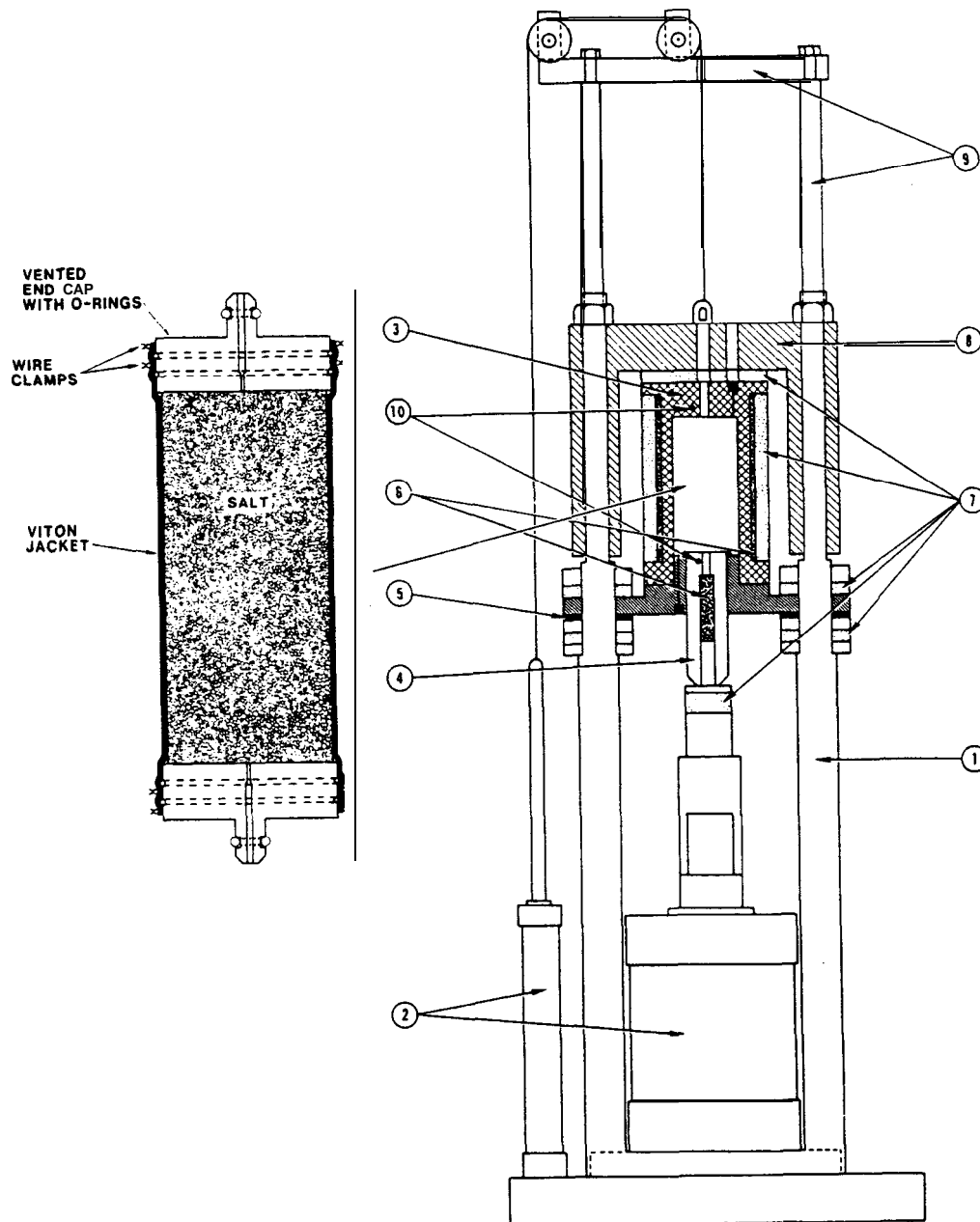


Figure 2 - Schematic of typical triaxial creep apparatus in Rock Mechanics Laboratory, Sandia National Laboratories.
Major components: (1) tie rods on base plate, (2) hydraulic actuators, (3) pressure vessel, (4) deviatoric loading piston, (5) Belleville washers, (6) heaters, (7) insulation, (8) cross head with guide rods, (9) frame extension/lifting fixture, (10) thermocouple location

After the machined and jacketed salt sample MB2 3349 was placed inside the triaxial creep apparatus, the fluid surrounding the entire sample was pressurized hydrostatically to 2000 psi (13.8 MPa). At that point, temperature was raised slowly to nominally 104°F (40°C) over a period of three hours. The sample was held at that temperature for approximately 12 hours to attain a homogeneous temperature state and to allow open cracks to close and heal. Crack closure and the removal of cracks results in the typical difference in the appearance of the undeformed and deformed samples (samples 3349 and 3350) in Figure 1. At the end of the pretest phase, axial load and, therefore, stress difference, τ , was applied in about 4 seconds to the desired value and then held fixed. After that, the progress of the test was monitored daily with manual records. Data were primarily taken and logged with a data acquisition system at least once an hour until it was decided to change the test parameters and proceed to the next experiment.

At the end of the fourth and last creep test, the applied stress difference was removed and the sample allowed to cool to room temperature under hydrostatic pressure. Heating and cooling of the salt under pressure avoided thermal stresses and attendant sample damage. In a final step, the deformed sample dimensions were recorded and the sample was photographed.

Experimental Results

All relevant test parameters and results are listed in Table 1. The creep rates at the end of each test are the average creep rates during the last approximately 15 hours before either the principal stress difference or the temperature were changed. They provide the best estimates of the steady-state creep rates at the prevailing conditions. A plot of the complete creep measurements is presented in Figure 3. The principal stress difference and confining pressure during the four experiments are plotted in Figure 4.

The values of the accumulated natural strains below and in Figure 3 denote changes in length with respect to current length as opposed to original sample length. These values are helpful in evaluating whether or not a particular creep test has reached the steady-state stage. Published accounts [8] indicate that steady-state creep may be established after as little as 0.01 (1%) strain at low temperature and only after as much as 0.3 (30%) strain at high temperature.

The listing of measurements for Moss Bluff salt was complemented by steady-state creep estimates for rock salt from the West Hackberry dome and the Bryan Mound dome. The latter values were calculated using published power law creep parameters. The response of rock salt from West Hackberry and Bryan Mound brackets the creep observations made on domal salts at Sandia National Laboratories.

TEJAS SALT, DEPTH 3349 FT

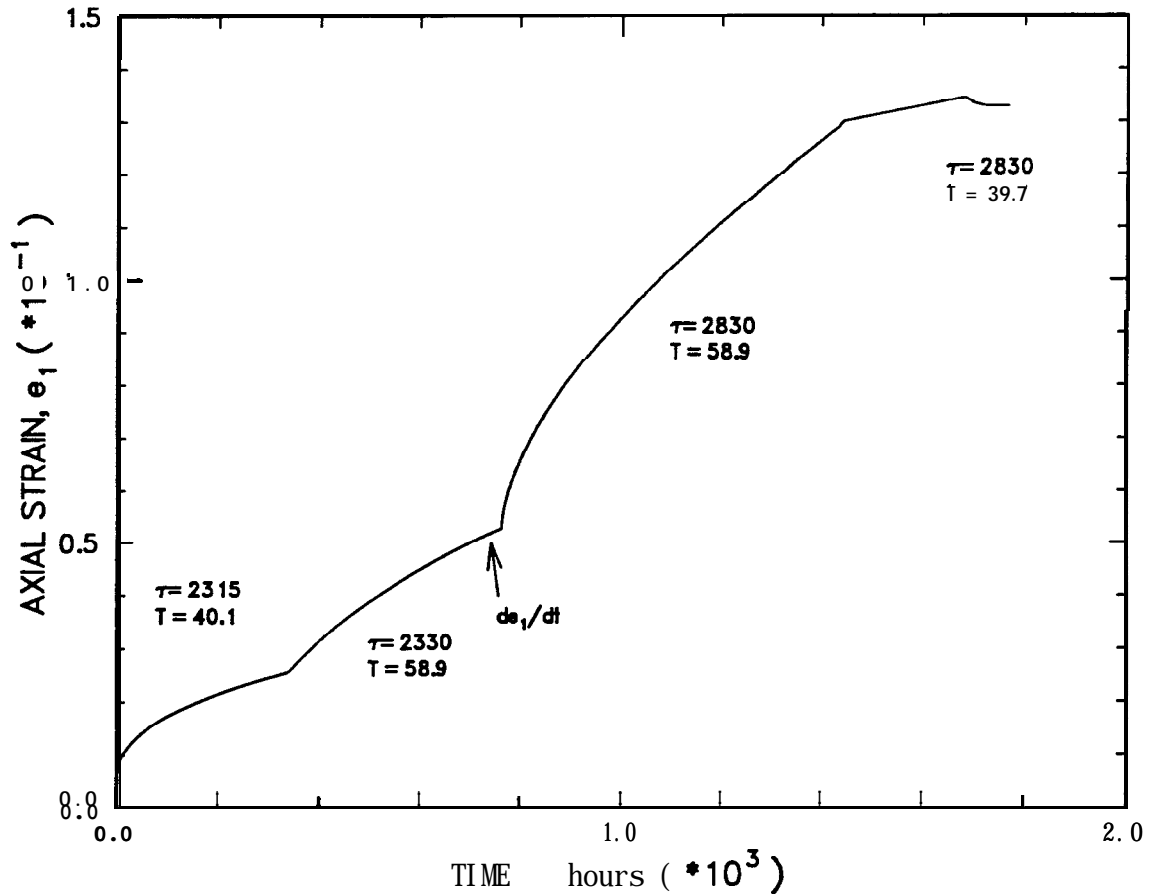


Figure 3 - Strain-time (creep) record for four creep experiments conducted on sample Moss Bluff 2, 3349 ft (1098.8 m) over a period of 1684 hours (70 days). Tail of curve was recorded during unloading and cooling portion of test. Steady-state creep

estimates were set equal to the slope $\frac{de_1}{dt} = \dot{e}_1$ near the end of each test.

TEJAS SALT, DEPTH 3349 FT

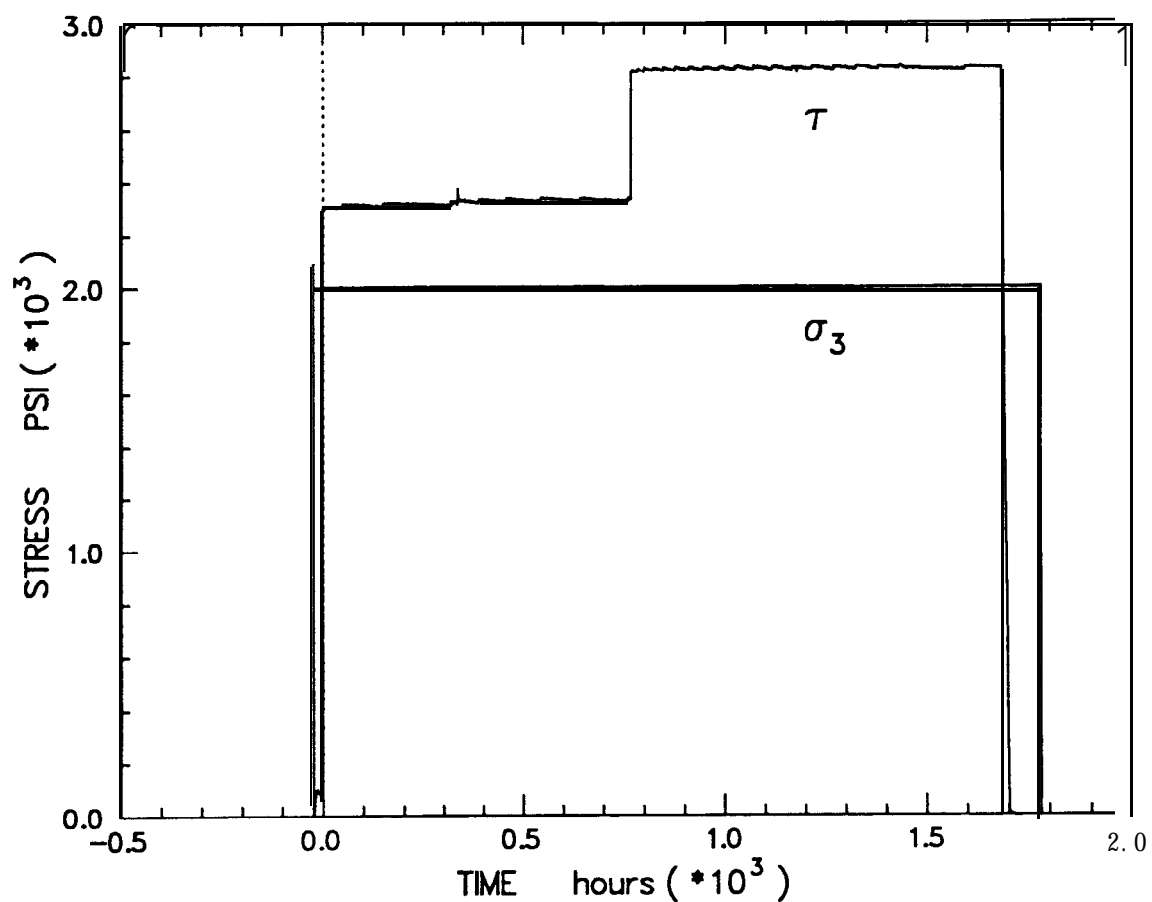


Figure 4 - Plot of principal stress difference, $\tau=(\sigma_1-\sigma_3)$, and confining pressure, σ_3 , versus time for triaxial creep experiments on Moss Bluff 2, 3349 ft (1098.8 m) over a period of 1684 hours (70 days). See also Figure 3.

Table 1 - Sample Data, Test Parameters,
and Creep Measurements for MB2

Initial sample dimensions:

Sample length, $L_0=8.103$ in (20.582 cm)
Sample diameter, $D_0=3.872$ in (9.835 cm)

Final sample dimensions:

$L_f=6.949$ in (17.650 cm)
 $D_f=4.187$ in (10.635 cm; average of 19 diameter measurements)
 $D_f=4.215$ in (10.706 cm; average of 15 diameter measurements excluding
measurements 0.25 in - 0.64 cm - away from either sample end).

Test I

Stress Difference	2315 psi
Confining Pressure	2000 psi
Temperature	40°C
Test duration	341 hrs
Accumulated natural strain e_1	2.54 %
Creep rate at end of test	7.42×10^{-9}
Comparison 8.8. creep estimate for West Hackberry salt (data set WH2)	7.97×10^{-9}
Comparison 8.8. creep estimate for Bryan Mound salt	3.33×10^{-10}

Stage II

Stress Difference	2330 psi
Confining Pressure	2000 psi
Temperature	60°C
Test duration	426 hrs
Accumulated natural strain e_1	2.72 %
Creep rate at end of test	1.18×10^{-8}
Comparison 8.8. creep estimate for West Hackberry salt	1.98×10^{-8}
Comparison 5.5. creep estimate for Bryan Mound salt	1.49×10^{-9}

Stage III

Stress Difference	2830 psi
Confining Pressure	2000 psi
Temperature	60°C
Test durations	676 hrs
Accumulated natural strain e_1	7.80 %
Creep rate at end of test	2.14×10^{-8}
Comparison 8.8. creep estimate for West Hackberry salt	5.44×10^{-8}
Comparison 8.5. creep estimate for Bryan Mound salt	3.60×10^{-9}

Stage IV

Nominal Stress Difference	2830 psi
Confining Pressure	2000 psi
Temperature	40°C
Test durations	241 hrs
Accumulated natural strain ϵ_1	0.40 %
Creep rate at end of test	5.21×10^{-9}
Comparison 8.8. creep estimate for West Hackberry salt	2.19×10^{-8}
Comparison 8.8. creep estimate for Bryan Mound salt	8.37×10^{-10}

The creep rate at the end of test IV was higher than the creep rate immediately after the temperature had been lowered from 140°F (60°C) to 104°F (40°C). The attendant very slow creep acceleration during stage IV indicates that the internal structure of the rock salt was recovering from a "harder" condition at the higher stress. It is suggested, therefore, that the creep rate at the end of stage IV was either lower or equal to, but by no means higher than the corresponding steady-state creep rate. Note that the creep rate listed for test I is higher than that for test IV indicating that the creep state at the end of test I was clearly transient.

Using the pairs of the observed creep rates towards the end of each test stage, the following activation energies and power-law stress exponent are obtained.

Stages I-II -- $Q = 4.77$ kcal/mole (19.87 kJ/mole)

Stages II-III -- $n = 2.96$

Stages III-IV -- $Q = 14.7$ kcal/mole (61.25 kJ/mole)

Normally, n could also be determined using test I and IV results. The unrealistically high upper bound steady-state creep estimate for test I precludes this comparison here.

A comparison of the present measurements for rock salt from Moss Bluff 2 with other salt data is given in Figure 5. In order to make this comparison useful, all data were normalized to 140°F (60°C). To do that for MB2 salt, both estimates of the activation energy, $Q=4.77$ and $Q=14.7$, were applied yielding the bar ranges shown. One of the bars is drawn as a dashed line to suggest that the lower Q -value and the resulting normalized steady-state creep estimates are abnormal and not credible.

It was stated that the present creep deformation measurements were restricted to axial sample deformation measurements on the assumption that the volumetric deformations would be negligible compared to the induced shear deformations. This assumption can be checked, at least crudely, by means of the external sample dimensions before and after the experiments. Figure 1 indicates that end friction prevented that the sample deformed perfectly homogeneously. The final diameter varied from the top through the middle to the bottom of the deformed sample MB2 3349 ft (1098.8 m).

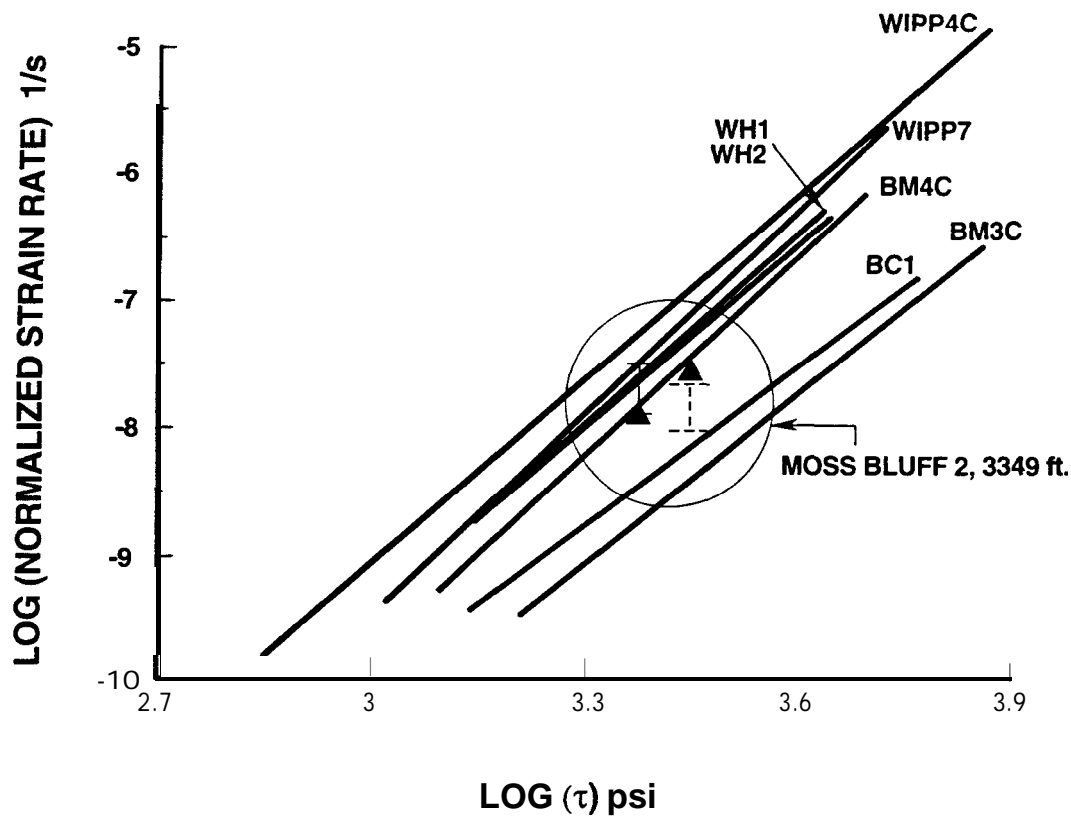


Figure 5 - Comparison of creep data for rock salt from Moss Bluff 2, 3349 ft (1098.8 m) with power-law fits to different sets of measurements on rock salt from the bedded Salado formation, southeastern New Mexico (WIPP4C and WIPP7), West Hackberry dome (WH1 and WH2), Bryan Mound dome (BM3C and BM4C), and Bayou Choctaw (BC1). All measurements and data fits represent steady-state creep estimates at the end of each test, ϵ_1 , normalized to creep at 140°F (60°C). Power-law parameters used for comparison data are published in Reference (2).

Making a total of nineteen diameter measurements at approximately 0.5, 1.5, and 2 in (1.3, 3.8, and 5.1 cm) from the sample ends, the average final diameter is 4.187 in (10.64 cm), and the final sample volume is 0.3% (0.28 in³; 4.59 cm³) greater than its starting volume. Omitting the diameter measurements closest to the sample ends as potentially unrepresentative, the deformed sample volume is computed to be 1.63% (1.5 in³; 2.46 cm³) greater than the undeformed volume. These changes are small compared with the measured shear deformations (shape changes) of more than 20%, 1.5 times the total accumulated axial strain $\epsilon_1 = 13.46\%$.

Discussion of Results

The conditions of the present tests fall into the domain of the low temperature behavior of rock salt which encompasses temperatures below approximately 40% of the melting temperature and well below the quasi-static ultimate stress [1,2]. Under these conditions, the power-law creep parameters, Equation 1, typically are $n=5$, and $Q=12-16$ kcal/mole (50-67 kJ/mole). Given repeat instrument calibrations and system checks, it is unlikely that the low values of n and Q in this study are caused by irregularities or errors in measurements. Rather, unusual derived creep parameters are attributed to the fact that the creep conditions in the present tests had not reached steady-state conditions. As a consequence, the creep rates at the ends of tests I and II (especially stage I) were only relatively crude upper bound estimates, and the creep rate at the end of stage IV a lower bound estimate for the steady-state creep underlying the use of Equation 1. This observation is neither new nor inconsistent with available data. For example, a West Hackberry salt sample subjected to very similar stresses at 140°F (60°C) had not reached steady state after an axial strain of more than 0.09 (9%).

Given the similarity of the activation energy $Q=14.7$ kcal/mole (61.3 kJ/mole) with published values, most credence can be placed in the results of tests III and IV. Going to the comparison Figure 5, therefore, it is strongly suggested that Moss Bluff 2 salt 3349 has creep characteristics intermediate to those of West Hackberry salt and Bryan Mound core, series BM3C, which was the most creep-resistant rock salt ever tested at Sandia National Laboratories. Taking the present observations one step further, if needed, complete creep parameters A , n , and Q (Equation 1) could be assigned for sensitivity studies using $Q=14.7$ kcal/mole (61.3 kJ/mole), $n=5$, and then estimating A numerically or graphically. For example, A can be calculated by means of Equation 1 and the creep rates at the end of tests III and IV. It follows that $A=9.92 \times 10^{15}$ 1/s (test III) and $A=9.98 \times 10^{15}$ 1/s (test IV).

Summary and Conclusions

Creep tests were performed on a representative sample of rock salt from borehole Moss Bluff 2 (MB2), Moss Bluff dome near Houston, Texas. The measurements were carried out on the request of Tejas Power Corporation. Four triaxial experiments were conducted at two values of principal stress difference and two temperatures. The confining pressure was 2000 psi (13.8 MPa) and constant throughout. The total test duration was 1684 hours (70 days) and the total accumulated axial, greatest compressive strain 0.135 (13.5%). Credible, smooth data were obtained in all tests. The minimum observed creep rates at the end of each test varied between 5.2×10^{-9} 1/s and 2.14×10^{-8} 1/s. The smallest creep rate translates into approximately 0.003 in (0.076 mm) of sample shortening per day.

The results obtained were evaluated in two ways. First, attempts were made to treat the smallest observed creep rates as steady-state creep rates and derive power-law steady-state creep parameters consisting of a power-law stress exponent, n , and a thermal activation energy, Q . Second, the measured creep rates at the end of each test were normalized to 140°F (60°C) and compared with power-law fits to data for rock salt from a bedded deposit and three other salt domes. Accordingly, it was found that $n=2.96$ and $4.77 \leq Q \leq 61.25$ kcal/mole (19.87 ≤ Q ≤ 61.25 kJ/mole). The abnormally low values of n and $Q=4.77$ kcal/mole (19.87 kJ/mole) were attributed to the fact that creep in at least two of the four tests was still in the transient stages rendering only crude overestimates of the steady-state creep rates under the prevailing conditions.

Graphical data comparisons suggest that the steady-state creep characteristics of MB2 salt, depth 3349 ft (1098.8 m), is bracketed by those of West Hackberry salt and Bryan Mound core which exhibited a more than thirteenfold difference in steady-state creep rates under the same conditions. Sensitivity computations could be conducted with the aid of Equation 1 and the parameter combination for MB2 salt: $A=9.95 \times 10^{15}$ 1/s, $Q=14.7$ kcal/K mole (61.3 kJ/mole), and $n=5$.

All measurements demonstrate the difficulties which still exist in evaluating the rate-dependent properties of rock salt for long-term predictions. Such predictions cannot rely on standard quasi-static material properties experiments.

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